AFRL-AFOSR-VA-TR-2016-0220

Search for Majorana Fermions in S-Wave Fermionic Superfluids

Chuanwei Zhang
UNIVERSITY OF TEXAS AT DALLAS

04/01/2016
Final Report

Air Force Research Laboratory
AF Office Of Scientific Research (AFOSR)/ RTB1
Arlington, Virginia 22203
Air Force Materiel Command

REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
10-03-2016	Final Report	Feb 1, 2015 - Jan 31, 2016

4. TITLE AND SUBTITLE	**5a. CONTRACT NUMBER**
Search for Majorana Fermions in S-Wave Fermionic Superfluids	
	5b. GRANT NUMBER FA9550-13-1-0045
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	**5d. PROJECT NUMBER**
Chuanwei Zhang Sumanta Tewari	**5e. TASK NUMBER**
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	**8. PERFORMING ORGANIZATION REPORT NUMBER**
Department of Physics, University of Texas at Dallas, Richardson, TX, 75080 Department of Physics and Astronomy, Clemson University, Clemson SC 29634	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	**10. SPONSOR/MONITOR'S ACRONYM(S)**
Air Force Office of Scientific Research 875 North Randolph Street Suite 325, Room 3112 Arlington VA, 22203	AFOSR
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

public available

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Majorana fermions (MFs) are quantum particles that are their own anti-particles, and satisfy non-Abelian exchange statistics. The latter is the key for their potential use in fault-tolerant topological quantum computation. In this project, we proposed to investigate the possibility of realizing MFs in much more physically robust s-wave superfluids by utilizing two additional components: spin-orbit coupling and Zeeman fields. In the last year grant period, we have made the following important achievements: 1) We found a large BKT transition temperature due to large effective superfluid densities in a spin-orbit coupled Fulde-Ferrell superfluid, making it possible to observe 2D Fulde-Ferrell superfluids at finite temperature; 2) Collaborated with Ian Speilman's group, we demonstrated the tunable spin-orbit coupling through the modulation of the Raman coupling strength in experiments; 3) We found that the spin-orbit coupled Fulde-Ferrell superfluids can support Weyl points or rings with nontrivial topological structures; 4) We proposed and experimentally realized a new type of tunable spin-orbit coupling using optical lattice band pseudospins. The research leads to 23 peer-reviewed publications, including 4 in Physical Review Letters and 1 in Nature Communications.

15. SUBJECT TERMS

Majorana fermions, s-wave superfluids, spin-orbit coupling, cold atoms, topological states, Weyl points

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(Include area code)*
U	U	U	UU		

Reset

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18
Adobe Professional 7.0

DISTRIBUTION A: Distribution approved for public release.

INSTRUCTIONS FOR COMPLETING SF 298

1. REPORT DATE. Full publication date, including day, month, if available. Must cite at least the year and be Year 2000 compliant, e.g. 30-06-1998; xx-06-1998; xx-xx-1998.

2. REPORT TYPE. State the type of report, such as final, technical, interim, memorandum, master's thesis, progress, quarterly, research, special, group study, etc.

3. DATES COVERED. Indicate the time during which the work was performed and the report was written, e.g., Jun 1997 - Jun 1998; 1-10 Jun 1996; May - Nov 1998; Nov 1998.

4. TITLE. Enter title and subtitle with volume number and part number, if applicable. On classified documents, enter the title classification in parentheses.

5a. CONTRACT NUMBER. Enter all contract numbers as they appear in the report, e.g. F33615-86-C-5169.

5b. GRANT NUMBER. Enter all grant numbers as they appear in the report, e.g. AFOSR-82-1234.

5c. PROGRAM ELEMENT NUMBER. Enter all program element numbers as they appear in the report, e.g. 61101A.

5d. PROJECT NUMBER. Enter all project numbers as they appear in the report, e.g. 1F665702D1257; ILIR.

5e. TASK NUMBER. Enter all task numbers as they appear in the report, e.g. 05; RF0330201; T4112.

5f. WORK UNIT NUMBER. Enter all work unit numbers as they appear in the report, e.g. 001; AFAPL30480105.

6. AUTHOR(S). Enter name(s) of person(s) responsible for writing the report, performing the research, or credited with the content of the report. The form of entry is the last name, first name, middle initial, and additional qualifiers separated by commas, e.g. Smith, Richard, J, Jr.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES). Self-explanatory.

8. PERFORMING ORGANIZATION REPORT NUMBER. Enter all unique alphanumeric report numbers assigned by the performing organization, e.g. BRL-1234; AFWL-TR-85-4017-Vol-21-PT-2.

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES). Enter the name and address of the organization(s) financially responsible for and monitoring the work.

10. SPONSOR/MONITOR'S ACRONYM(S). Enter, if available, e.g. BRL, ARDEC, NADC.

11. SPONSOR/MONITOR'S REPORT NUMBER(S). Enter report number as assigned by the sponsoring/ monitoring agency, if available, e.g. BRL-TR-829; -215.

12. DISTRIBUTION/AVAILABILITY STATEMENT. Use agency-mandated availability statements to indicate the public availability or distribution limitations of the report. If additional limitations/ restrictions or special markings are indicated, follow agency authorization procedures, e.g. RD/FRD, PROPIN, ITAR, etc. Include copyright information.

13. SUPPLEMENTARY NOTES. Enter information not included elsewhere such as: prepared in cooperation with; translation of; report supersedes; old edition number, etc.

14. ABSTRACT. A brief (approximately 200 words) factual summary of the most significant information.

15. SUBJECT TERMS. Key words or phrases identifying major concepts in the report.

16. SECURITY CLASSIFICATION. Enter security classification in accordance with security classification regulations, e.g. U, C, S, etc. If this form contains classified information, stamp classification level on the top and bottom of this page.

17. LIMITATION OF ABSTRACT. This block must be completed to assign a distribution limitation to the abstract. Enter UU (Unclassified Unlimited) or SAR (Same as Report). An entry in this block is necessary if the abstract is to be limited.

Final Progress Report for Award # FA9550-13-1-0045

Period: 02/01/2013-01/31/2016

Title: Search for Majorana Fermions in S-Wave Fermionic Superfluids

PI: Chuanwei Zhang, University of Texas at Dallas

Co-PI: Sumanta Tewari, Clemson University

Program manager: Dr. Tatjana Curcic, Atomic and molecular physics

Objectives and research goals

Majorana fermions were envisioned by E. Majorana in 1935 to describe neutrinos. The Majorana fermions are intriguing because they can be construed as their own anti-particles, unlike Dirac fermions where electrons and positrons (holes) are distinct. Although the emergence of Majorana excitations in physical systems is by itself a truly extraordinary phenomenon, a great deal of recent attention has also been focused on them due to their potential use in fault tolerant topological quantum computation (TQC). However, despite the tremendous technological potential, Majorana fermions have proven to be hard to observe in natural physical systems such as quantum Hall systems and chiral *p*-wave superconductors/superfluids.

In this project, we proposed to investigate the possibility of realizing Majorana fermions in much more physically robust *s*-wave superfluids by utilizing two additional components: spin-orbit coupling and Zeeman fields. Cold atomic superfluids are excellent platforms for implementing this technique because of the tunability of various parameters as well as the absence of disorder. We proposed to develop concrete experimental procedures and theoretical foundation necessary for observing Majorana fermions and the associated topological phase transitions using experimental techniques which have already been realized for ultra-cold atomic gases.

In the three year grant period, we have made great achievements for realizing the ideas and schemes proposed in the original proposal. In total, we have published over 40 peer-reviewed publications, including 1 in Nature Physics, 3 in Nature Communications, and 7 in Physical Review Letters. Research accomplishments in previous two year grant periods have been reported in details in previous annual reports, therefore here we focus on the last year grant period. In the last year grant period, we have made the following important achievements.

Important achievements:

1. Berezinskii-Kosterlitz-Thouless Phase Transition in 2D Spin-Orbit Coupled Fulde-Ferrell Superfluids

Yong Xu and Chuanwei Zhang

Phys. Rev. Lett. 114, 110401 (2015).

The experimental observation of traditional Zeeman-field induced Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) superfluids has been hindered by various challenges, in particular, the requirement of low dimension systems. In 2D, it is well known that finite temperature phase fluctuations lead to extremely small Berezinskii-Kosterlitz-Thouless (BKT) transition temperature, raising serious concern regarding the observability of 2D FFLO superfluids.

Recently, it was shown that FFLO superfluids can be realized using a Rashba spin-orbit coupled Fermi gas subject to Zeeman fields, which may also support topological excitations such as Majorana fermions in 2D. Here we address the finite temperature BKT transition issue in this system, which may exhibits gapped, gapless, topological, and gapless topological FF phases. We find a large BKT transition temperature due to large effective superfluid densities, making it possible to observe 2D FF superfluids at finite temperature. In addition, we show that gapless FF superfluids can be stable due to their positive superfluid densities. These findings pave the way for the experimental observation of 2D gapped and gapless FF superfluids and their associated topological excitations at finite temperature.

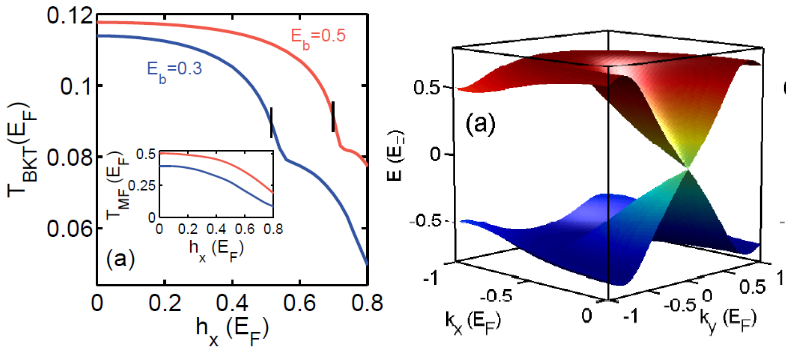

Figure 1: (Left) The change of the BKT transition temperature with respect to the in-plane Zeeman field. (Right) The quasiparticle excitation at the critical point from normal superfluids to topological superfluids.

2. Structured Weyl Points in Fulde-Ferrell Superfluids,

Yong Xu, Fan Zhang, Chuanwei Zhang,

Phys. Rev. Lett. 115, 265304 (2015)

Weyl fermions were initially conceived to describe neutrinos in particle physics. Recently, Weyl fermions have been widely examined in a class of solid-state materials dubbed as Weyl semimetals. Remarkably, these semimetals can be described by Weyl Hamiltonian near their unusual Weyl points, where two linearly dispersed bands cross. In this paper, We demonstrate, for the first time, that a Weyl point can develop a pair of non-degenerate gapless spheres. Such a bouquet of two spheres is characterized by three distinct topological invariants of manifolds with full energy gaps, i.e., the Chern number of a 0D point inside one developed sphere, the winding number of a 1D loop around the original Weyl point, and the Chern number of a 2D surface enclosing the whole bouquet. We show that such structured Weyl points can be realized in the Fulde-Ferrell superfluid quasiparticle spectrum of a 3D degenerate Fermi gas subject to spin-orbit couplings and Zeeman fields.

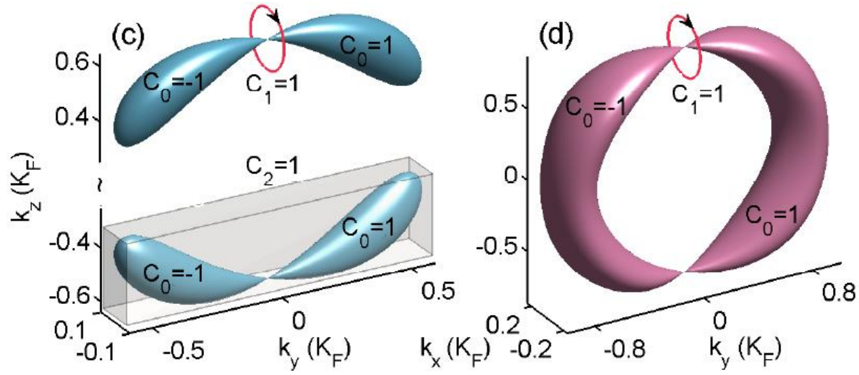

Figure 2: (Left) Structured Weyl points in a FF superfluid. C0, C1, and C2 are three different types of topological Chern numbers. (Right) Connected structured Weyl points.

3. Tunable Spin-Orbit Coupling via Strong Driving in Ultracold Atom Systems,
K. Jiménez-García, L. J. LeBlanc, R. A. Williams, M. C. Beeler, C. Qu, M. Gong, C. Zhang, I. B. Spielman,
Phys. Rev. Lett. 114, 125301 (2015),
PRL Editors' Suggestions
See **Physics News and Commentary**: On demand spin-orbit coupling by Michael Schirber

The properties of electronic materials are deeply entwined with their bandstructure or more generally, their single-particle spectrum, which gives rise to: conductors, semiconductors, conventional insulators and now topological insulators. Understanding and controlling bandstructure in new ways therefore allows access to new phenomena. Spin-orbit coupling (SOC) plays a fundamental role in most topological materials, linking the spin and the momentum of quantum particles. In ultracold atom systems we precisely design, introduce and manipulate SOC by coupling the internal atomic degrees of freedom with laser. Here, we illuminated an ultracold atom system with a pair of Raman lasers, inducing SOC in an effective two-level system with SOC strength defined by the laser geometry alone. In this letter, we experimentally show that strongly modulating the Raman coupling tunes the SOC strength, independently of geometry and in agreement with theory.

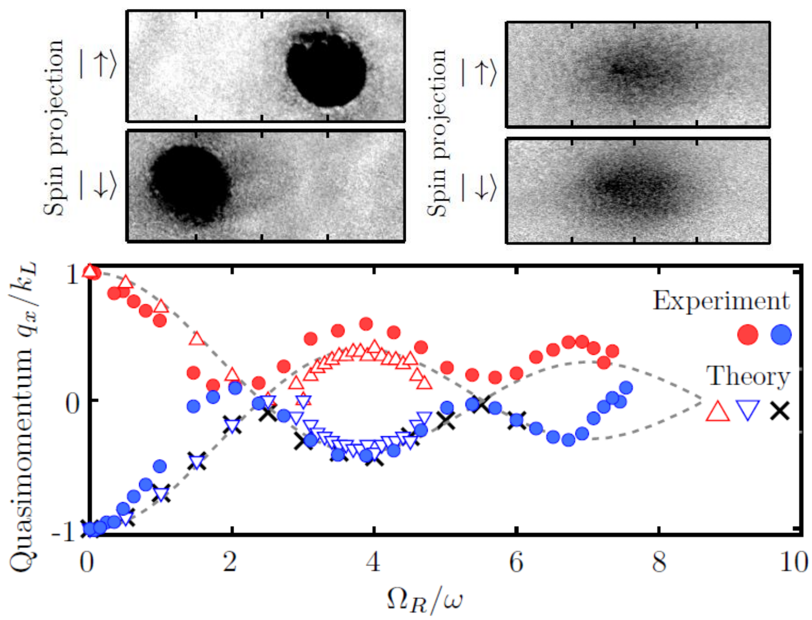

Figure 3: Top: Atom distributions without (left) and with (right) tuning the SOC strength. Bottom: change of the quasimomentum due to tunable SOC.

4. Fulde-Ferrell superfluids without spin imbalance in driven optical lattices

Zhen Zheng, Chunlei Qu, Xubo Zou, and Chuanwei Zhang

arXiv:1501.00448, **Phys. Rev. Lett. (in press 2016)**

Spin-imbalanced ultra-cold Fermi gases have been widely studied recently as a platform for exploring the long-sought Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) superfluid phases, but so far conclusive evidence has not been found. Here we propose to realize an FF superfluid without spin imbalance in a three-dimensional (3D) fermionic cold atom optical lattice, where s- and p-orbital bands of the lattice are coupled by another weak moving optical lattice. Such coupling leads to a spin-independent asymmetric Fermi surface, which, together with the s-wave scattering interaction between two spins, yields an FF type of superfluid pairing. Unlike traditional schemes, our proposal does not rely on the spin imbalance (or an equivalent Zeeman field) to induce the Fermi surface mismatch and provides a completely new route for realizing FF superfluids. The proposed experimental scheme for generating asymmetric band structure has been realized in experiments for a BEC (see the achievement 5 below).

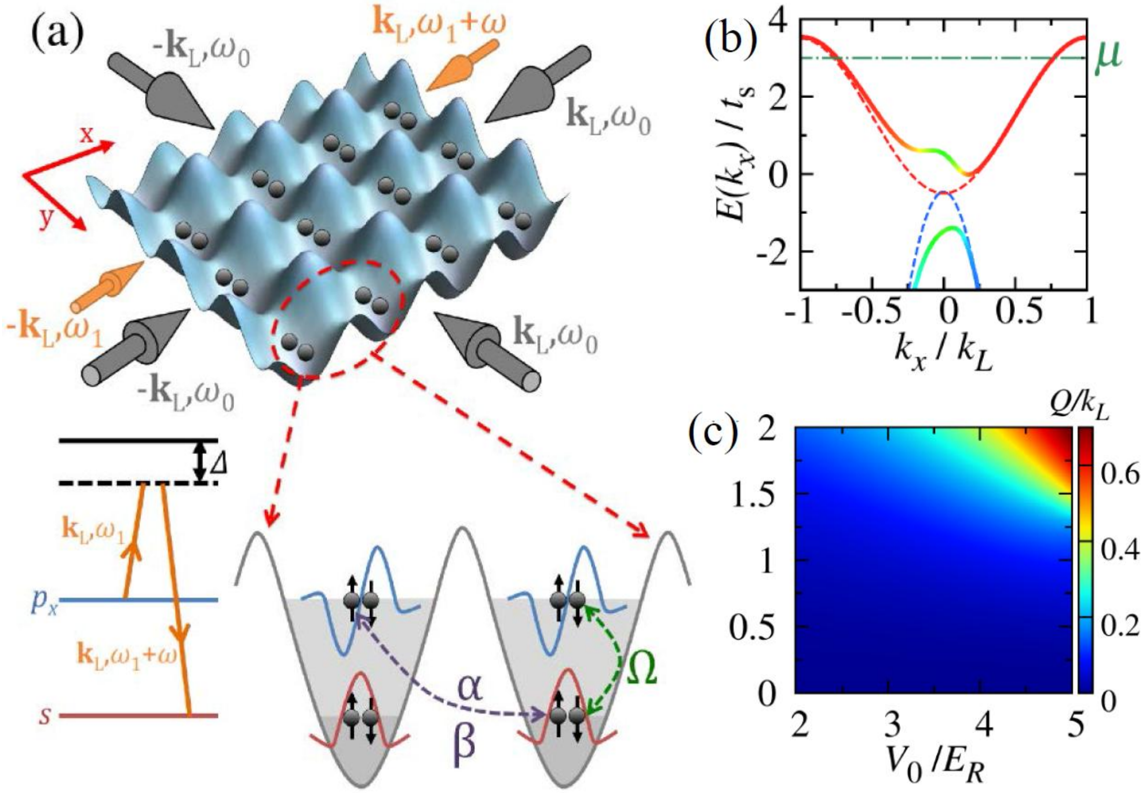

Figure 4: (a) Proposed experimental setup and level diagram for realizing FF superfluids in driven optical lattices. (b) The resulting asymmetric band structure due to the coupling between s- and p-bands. (c) The dependence of the Cooper pair momentum Q on lattice parameters.

5. Spin-momentum coupled Bose-Einstein condensates with lattice band pseudospins
M. A. Khamehchi, Chunlei Qu, M. E. Mossman, Chuanwei Zhang, P. Engels,
Nature Communications 7, 10867 (2016)

The quantum emulation of spin-momentum coupling, a crucial ingredient for the emergence of topological phases, is currently drawing considerable interest. In previous quantum gas experiments, typically two atomic hyperfine states were chosen as pseudospins. Here, we report the observation of a spin-momentum coupling achieved by loading a Bose-Einstein condensate into periodically driven optical lattices. The s and p bands of a static lattice, which act as pseudospins, are coupled through an additional moving lattice that induces a momentum-dependent coupling between the two pseudospins, resulting in s–p hybrid Floquet-Bloch bands. We investigate the band structures by measuring the quasimomentum of the Bose-Einstein condensate for different velocities and strengths of the moving lattice, and compare our measurements to theoretical predictions. The realization of spin-momentum coupling with lattice bands as pseudospins paves the way for engineering novel quantum matter using hybrid orbital bands.

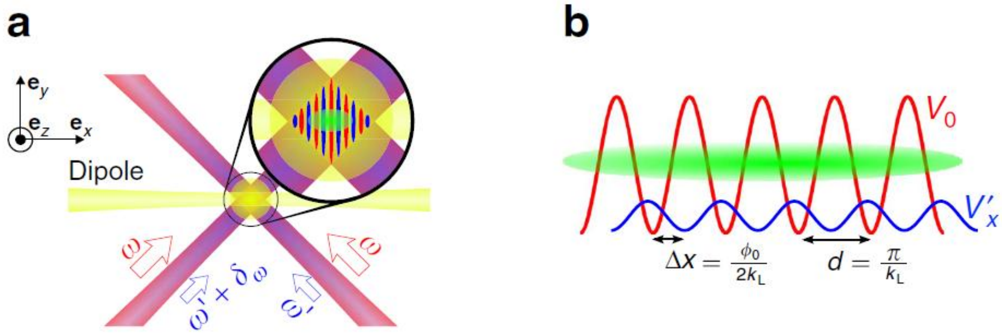

Figure 5: Experimental setup for realizing the spin-momentum coupling with lattice band pseudospins.

6. Spin–orbital-angular-momentum coupling in Bose-Einstein condensates,
Kuei Sun, Chunlei Qu, **Chuanwei Zhang**
Phys. Rev. A 91, 063627 (2015)

& **Quantum phases of Bose-Einstein condensates with synthetic spin-orbital-angular-momentum coupling**
Chunlei Qu, Kuei Sun, **Chuanwei Zhang**,
Phys. Rev. A 91, 053630 (2015)

Spin-orbit coupling (SOC) plays a crucial role in many branches of physics. In this context, the recent experimental realization of the coupling between spin and linear momentum of ultracold atoms opens a completely new avenue for exploring new spin-related superfluid physics. We proposed that another important and fundamental SOC, the coupling between spin and orbital angular momentum (SOAM), can be implemented for ultracold atoms using higher-order Laguerre-Gaussian laser beams to induce Raman coupling between two hyperfine spin states of atoms. We studied the ground-state phase diagrams of SOAM-coupled Bose-Einstein condensates on a ring trap and explored their applications in gravitational force detection.

In addition, we studied quantum phases of a realistic Bose-Einstein condensate (BEC) with this synthetic SOAM coupling in a disk-shaped geometry, respecting radial inhomogeneity of the Raman coupling. We found that the experimental system naturally resides in a strongly interacting regime in which the phase diagram significantly deviates from the single-particle picture. The interplay between SOAM coupling and interaction leads to rich structures in spin-resolved position and momentum distributions, including a stripe phase and various types of immiscible states. Our results may provide the basis for further investigation of intriguing superfluid physics induced by SOAM coupling as well as guide the experimental investigation of SOAM-coupled BECs. Experimental investigation of such SOAM coupling is ongoing in several groups.

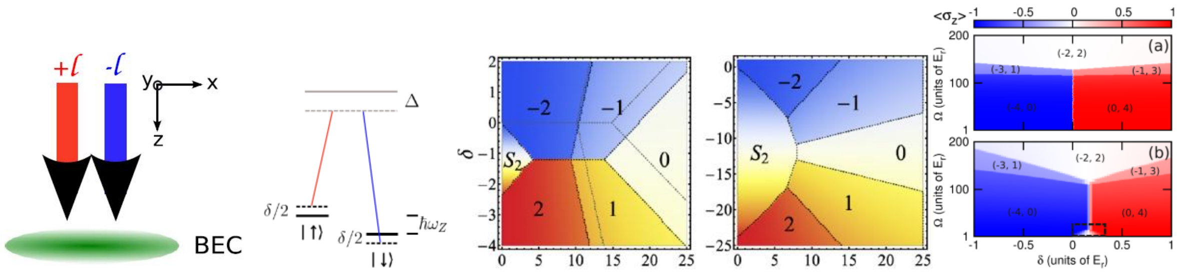

Figure 3: (1,2) Laser setup and level diagram for realizing SOAM coupling. (3-4) Phase diagram for a SOAM coupled BEC on a ring. (5) Phase diagram for a SOAM coupled BEC in a disk shape.

7: Tunneling conductance for Majorana fermions in spin-orbit coupled semiconductor-superconductor heterostructures using superconducting leads

G. Sharma, S. Tewari
arXiv: 1510.07737

It has been recently pointed out that the use of a superconducting (SC) lead instead of a normal metal lead can suppress the thermal broadening effects in tunneling conductance from Majorana fermions, helping reveal the quantized conductance of $2e^2/h$ which is taken as a smoking gun signature of Majorana quasiparticles. In this work we discuss the specific case of tunneling conductance with SC leads of spin-orbit coupled semiconductor-superconductor (SM-SC) heterostructures in the presence of a Zeeman field, a system which has been extensively studied both theoretically and experimentally using a metallic lead. We examine the dI/dV spectra using a SC lead for different sets of physical parameters including temperature, tunneling strength, wire length, magnetic field, and induced SC pairing potential in the SM nanowire. We conclude that in a finite wire the Majorana splitting energy ΔE, which has non-trivial dependence on these physical parameters, remains responsible for the dI/dV peak broadening, even when the temperature broadening is suppressed by the SC gap in the lead. In a finite wire the signatures of Majorana fermions with a SC lead are oscillations of quasi-Majorana peaks about bias V = $\pm\Delta_{\text{lead}}$, in contrast to the case of metallic leads where such oscillations are about zero bias. Our results will be useful for analysis of future experiments on SM-SC heterostructures using SC leads.

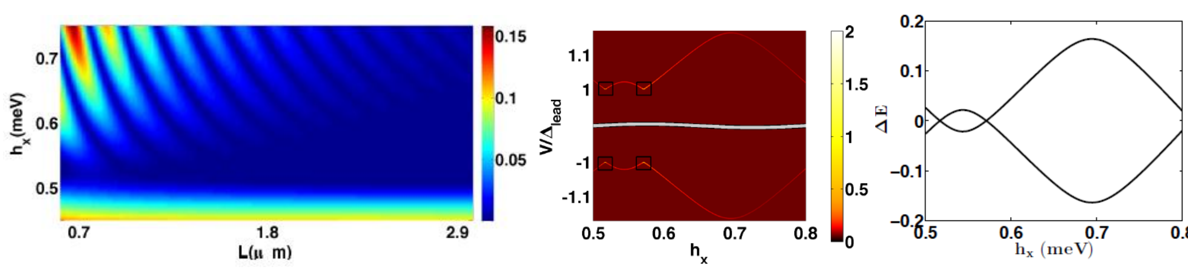

Fig.7. Left: Majorana splitting energy ΔE as a function of length of the wire L and applied magnetic field h_x, showing oscillations for small L values, for a wide range of h_x above the topological phase transition at $h_x = 0.5$ meV. The amplitude of oscillations in ΔE subsequently suppressed for wires with longer length. The value of SC gap chosen for these plots was Δ= 0.5 eV, and the color bar on the right is in the units of meV. Middle: Majorana dI/dV profile with a superconducting lead for a short wire of length $L = 0.5\ \mu m$, showing oscillations about $V =$

$\pm\Delta_{lead}$ as a function of magnetic field h_x (in meV). The color bar on the right is in the unit of e^2/h and the value of SC gap chosen was $\Delta = 0.5$meV. The four square boxes highlight the regions where the quantized peak height of magnitude $G_M = (4-\pi)\, e^2/h$ should be observed. Right: The energy splitting ΔE (in meV) as a function of h_x for the same system, showing oscillations about zero energy. In an experiment done with a normal metallic lead instead of a superconducting lead, the oscillations will be about zero bias voltage in a similar fashion as displayed here.

8: Spin polarization of Majorana zero modes and topological quantum phase transition in semiconductor Majorana nanowires

T. D. Stanescu, S. Tewari

arXiv: 1603.02255

A number of recent works have discussed the issue of spin polarization of a Majorana zero mode in low temperature systems. In this work we show that the spin polarization density of a Majorana zero mode, computed as an average of the spin operator over its wave function, is identically zero. A single non-degenerate Majorana zero mode, therefore, does not couple to an applied magnetic field, except via hybridization with higher energy excited states (if present), which may perturb its wave function. If spin is defined by considering only the particle components of the wave function, as has been done in some recent works, Majorana zero modes do have a non-zero spatial profile of this quantity, which is measurable in scanning tunneling microscopy (STM) experiments. However, if such a quantity is measured in spin-resolved tunneling experiments (without spatial resolution), we show that it cannot be used as a unique signature of Majorana zero modes in the topologically non-trivial phase. As a byproduct, we show in this work that in spatially inhomogeneous systems (specifically, in systems with a soft boundary), accidental zero energy modes (which for all practical purposes behave as Majorana zero modes) can appear with increasing magnetic field even in the absence of a topological quantum phase transition (TQPT). But only after gap closing and the associated TQPT, the modes are localized near the system edges, resulting in the maximum topological protection. In light of these considerations, demonstrating the nonlocal character of the topologically-protected Majorana pair and its emergence after the systems undergo a TQPT, become critical tasks for the ongoing experimental search for Majorana bound states in low temperature systems.

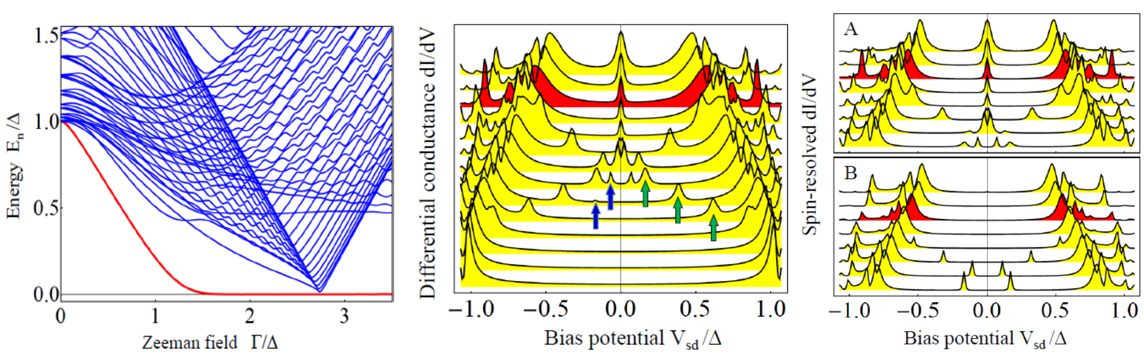

Fig. 8. Left: Dependence of the low-energy BdG spectrum on the applied Zeeman field for a system of superconducting chains with smooth confinement. Only the positive energies are shown. Note the vanishing of the bulk gap (blue lines) at the critical field $\Gamma = \Gamma_c \sim 2.7\ \Delta$, which signals a topological quantum phase transition. Note that remarkable result that the zero-energy

mode extends into the topologically trivial phase for $\Gamma < \Gamma$. Middle: Differential conductance as a function of the bias potential for different values of the Zeeman field ranging from $\Gamma = 0$ (lowest curve) to $\Gamma = 3.5\ \Delta$ (top curve) in steps of $0.25\ \Delta$. The curves have been shifted for clarity. The red-filled curve corresponds to $\Gamma = \Gamma \sim 2.75\ \Delta$; note the absence of any signature associated with the closing of the bulk gap and the emergence of a zero-bias peak for $\Gamma < \Gamma$ (i.e. in the topologically-trivial regime). The peaks marked by blue arrows, which merge into the zero-bias peak, correspond to the lowest energy mode (red line) in top left, while the peaks marked by green arrows are associated with Andreev bound states localized inside the potential barrier region. Right: Differential conductance for spin-resolved tunneling into the end of the wire. The Zeeman field ranges from $\Gamma = 1.5\ \Delta$ (lowest curves) to $\Gamma = 3.25\ \Delta$ (top curves) in steps of $0.25\ \Delta$. Panel A corresponds to the tunneling of electrons with spin parallel to the applied Zeeman field, while panel B shows the differential conductance corresponding to the opposite spin orientation. Note that that the zero bias peak is absent when tunneling electrons with a spin-orientation opposite to the spin polarization of the leftmost Majorana bound state.

Publications supported by the grant in this period (include 4 Phys. Rev. Lett., 1 Nature Communications, 10 Phys. Rev. A and B, 1 Scientific Reports, 1 selected as PRL Editors' Suggestions and reported by Physics News and Commentary)
Underlined authors: graduate students and postdoctors supervised by the PIs.

1. Yong Xu, **Chuanwei Zhang**, *Dirac and Weyl Rings in Three Dimensional Cold Atom Optical Lattices*,
arXiv:1510.03355
2. Zengming Meng, Lianghui Huang, Peng Peng, Donghao Li, Liangchao Chen, Yong Xu, **Chuanwei Zhang**, Pengjun Wang, Jing Zhang, *Experimental observation of topological band gap opening in ultracold Fermi gases with two-dimensional spin-orbit coupling*,
arXiv:1511.08492
3. Beibing Huang, Pak Hong Chui, Jia Liu, **Chuanwei Zhang**, Ming Gong, *Topological superfluids with time-reversal symmetry from s-wave interaction in a bilayer system*,
arXiv:1511.01713
4. Lei Jiang, Chunlei Qu, **Chuanwei Zhang**, *1D topological chains with Majorana fermions in 2D non-topological optical lattices*,
arXiv:1503.01810
5. Zhen Zheng, Chunlei Qu, Xubo Zou, **Chuanwei Zhang**, *Fulde-Ferrell superfluids without spin-imbalance in three-dimensional driven spinful fermionic optical lattices*,
arXiv:1501.00448, to appear in Phys. Rev. Lett.
6. Kuei Sun, Chunlei Qu, Yong Xu, Yongping Zhang, **Chuanwei Zhang***, *Interacting spin-orbit-coupled spin-1 Bose-Einstein condensates*,
Phys. Rev. A 93, 023615 (2016).
7. M. A. Khamehchi, Chunlei Qu, M. E. Mossman, **Chuanwei Zhang***, P. Engels*, *Spin-momentum coupled Bose-Einstein condensates with lattice band pseudospins*,
Nature Communications 7, 10867 (2016)
8. Yong Xu, Fan Zhang, **Chuanwei Zhang***, *Structured Weyl Points in Spin-Orbit Coupled Fermionic Superfluids*,
Phys. Rev. Lett. 115, 265304 (2015)

9. Yuri Gartstein*, Xiao Li, and **Chuanwei Zhang***, *Exciton-polaritons in transition-metal dichalcogenides and their direct excitation via energy transfer*, Phys. Rev. B 92, 075445 (2015)
10. Chunlei Qu, Ming Gong, Yong Xu, **Sumanta Tewari**, **Chuanwei Zhang***, *Majorana fermions in quasi-one-dimensional and higher-dimensional ultracold optical lattices* Phys. Rev. A 92, 023621 (2015)
11. Yong Xu, Yongping Zhang, **Chuanwei Zhang***, *Bright solitons in a 2D spin-orbit-coupled dipolar Bose-Einstein condensate*, Phys. Rev. A 92, 013633 (2015)
12. Yan Li, Chunlei Qu, Yongsheng Zhang, **Chuanwei Zhang***, *Dynamical spin-density waves in a spin-orbit-coupled Bose-Einstein condensate*, Phys. Rev. A 92, 013635 (2015)
13. Kuei Sun, Chunlei Qu, **Chuanwei Zhang***, *Spin–orbital-angular-momentum coupling in Bose-Einstein condensates* Phys. Rev. A 91, 063627 (2015)
14. Chunlei Qu, Kuei Sun, **Chuanwei Zhang***, *Quantum phases of Bose-Einstein condensates with synthetic spin-orbital-angular-momentum coupling*, Phys. Rev. A 91, 053630 (2015)
15. Zhen Zheng, Chunlei Qu, Xubo Zou, **Chuanwei Zhang***, *Floquet FFLO superfluids and Majorana fermions in a shaken fermionic optical lattice*, Phys. Rev. A 91, 063626 (2015)
16. Ming Gong, Yinyin Qian, V. W. Scarola, **Chuanwei Zhang***, *Dzyaloshinskii-Moriya Interaction and Spiral Order in Spin-orbit Coupled Optical Lattices*, Scientific Reports 5, 10050 (2015)
17. K. Jiménez-García, L. J. LeBlanc, R. A. Williams, M. C. Beeler, C. Qu, M. Gong, **C. Zhang**, I. B. Spielman, *Tunable Spin-Orbit Coupling via Strong Driving in Ultracold Atom Systems*, Phys. Rev. Lett. 114, 125301 (2015), **Editors' Suggestions, Featured in Physics**
    See **Physics News and Commentary**: "*On demand spin-orbit coupling*" by Michael Schirber
18. Yong Xu, **Chuanwei Zhang***, *Berezinskii-Kosterlitz-Thouless Phase Transition in 2D Spin-Orbit Coupled FF Superfluids*, Phys. Rev. Lett. 114, 110401 (2015).
19. G. Sharma, **S. Tewari**, P. Goswami, Victor M. Yakovenko, S. Chakravarty, *A Calculation of polar Kerr effect in high temperature cuprate superconductors*, Phys. Rev. B 93, 075156 (2016).
20. G. Sharma, P. Goswami, **S. Tewari**, *Nernst and magneto-thermal conductivity in a lattice model of Weyl fermions*, Phys. Rev. B 93, 035116 (2016).
21. G. Sharma, **S. Tewari**, *Tunneling conductance for Majorana fermions in spin-orbit coupled semiconductor-superconductor heterostructures using superconducting leads*, arXiv: 1510.07737
22. K. Seo, J. D. Sau, **S. Tewari**, *Robust Zero Energy Bound States Localized at Magnetic Impurities in Iron-based Superconductors*, arXiv: 1512.03450

23. T. D. Stanescu, and S. Tewari, *Spin polarization of Majorana zero modes and topological quantum phase transition in semiconductor Majorana nanowires*, arXiv:1603.02255

Invited talks

- **PI Chuanwei Zhang**

1. *Fulde-Ferrell Superfluids in Degenerate Fermi Gases with Synthetic Gauge Fields*, Condensed Matter Seminar, The University of California at San Diego, Oct 2015, San Diego, California
2. *Majorana fermions and topological quantum computation*, Physics Colloquium, The University of Texas at San Antonio, Sep 2015, San Antonio, Texas
3. *Fulde-Ferrell Superfluids in Degenerate Fermi Gases with Synthetic Gauge Fields*, AMO seminar, Eastern China Normal University, June 2015, Shanghai, China
4. *Majorana fermions and topological quantum computation*, Physics Colloquium, Eastern China Normal University, June 2015, Shanghai, China
5. *Fulde-Ferrell Superfluids in Degenerate Fermi Gases with Synthetic Gauge Fields*, Seminar in Wilczek Quantum Center, Zhejiang University of Technology, May 2015, Hangzhou, China
6. *Fulde-Ferrell Superfluids in Degenerate Fermi Gases with Synthetic Gauge Fields*, AMO seminar, University of Science and Technology of China, May 2015, Hefei, China
7. *Fulde-Ferrell Superfluids in Degenerate Fermi Gases with Synthetic Gauge Fields*, Condensed Matter Seminar, Beijing University, May 2015, Beijing, China
8. *Fulde-Ferrell Superfluids in Degenerate Fermi Gases with Synthetic Gauge Fields*, AMO seminar, Shanxi University, May 2015, Taiyuan, China
9. *Majorana fermions and topological quantum computation*, Physics Colloquium, Physics Colloquium, Shanxi University, May 2015, Taiyuan, China
10. *Fulde-Ferrell Superfluids in Degenerate Fermi Gases with Synthetic Gauge Fields*, American Physical Society March Meeting invited talk, March 2015, San Antonio, Texas

- **PI Sumanta Tewari**

1. *Lectures/short course (3 lectures) on Majorana fermions in topological superconductors/superlfuids,* Indian Institute of Science Education and Research (IISER), Pune, India, August, 2015
2. *"Quest for the quirky quantum particle comes good: Search for Majorana fermions in topological superconductors",* Indian Institute of Science Education and Research (IISER), Pune, India, August, 2015

1.

1. Report Type

Final Report

Primary Contact E-mail
Contact email if there is a problem with the report.

chuanwei.zhang@utdallas.edu

Primary Contact Phone Number
Contact phone number if there is a problem with the report

972-883-4520

Organization / Institution name

University of Texas at Dallas

Grant/Contract Title
The full title of the funded effort.

Search for Majorana Fermions in S-Wave Fermionic Superfluids

Grant/Contract Number
AFOSR assigned control number. It must begin with "FA9550" or "F49620" or "FA2386".

FA9550-13-1-0045

Principal Investigator Name
The full name of the principal investigator on the grant or contract.

Chuanwei Zhang

Program Manager
The AFOSR Program Manager currently assigned to the award

Tatjana Curcic

Reporting Period Start Date

02/01/2013

Reporting Period End Date

01/31/2016

Abstract

Majorana fermions (MFs) are quantum particles that are their own anti-particles, and satisfy non-Abelian exchange statistics. The latter is the key for their potential use in fault-tolerant topological quantum computation. In this project, we proposed to investigate the possibility of realizing MFs in much more physically robust s-wave superfluids by utilizing two additional components: spin-orbit coupling and Zeeman fields. In the last year grant period, we have made the following important achievements: 1) We found a large BKT transition temperature due to large effective superfluid densities in a spin-orbit coupled Fulde-Ferrell superfluid, making it possible to observe 2D Fulde-Ferrell superfluids at finite temperature; 2) Collaborated with Ian Speilman's group, we demonstrated the tunable spin-orbit coupling through the modulation of the Raman coupling strength in experiments; 3) We found that the spin-orbit coupled Fulde-Ferrell superfluids can support Weyl points or rings with nontrivial topological structures; 4) We proposed and experimentally realized a new type of tunable spin-orbit coupling using optical lattice band pseudospins. The research leads to 23 peer-reviewed publications, including 4 in Physical Review Letters and 1 in Nature Communications.

Distribution Statement
This is block 12 on the SF298 form.

Distribution A - Approved for Public Release

Explanation for Distribution Statement

If this is not approved for public release, please provide a short explanation. E.g., contains proprietary information.

SF298 Form

Please attach your SF298 form. A blank SF298 can be found here. Please do not password protect or secure the PDF The maximum file size for an SF298 is 50MB.

SF-298-2016.pdf

Upload the Report Document. File must be a PDF. Please do not password protect or secure the PDF . The maximum file size for the Report Document is 50MB.

report2016-afosr-final.pdf

Upload a Report Document, if any. The maximum file size for the Report Document is 50MB.

Archival Publications (published) during reporting period:

See report

Changes in research objectives (if any):

Change in AFOSR Program Manager, if any:

Extensions granted or milestones slipped, if any:

AFOSR LRIR Number

LRIR Title

Reporting Period

Laboratory Task Manager

Program Officer

Research Objectives

Technical Summary

Funding Summary by Cost Category (by FY, $K)

	Starting FY	FY+1	FY+2
Salary			
Equipment/Facilities			
Supplies			
Total			

Report Document

Report Document - Text Analysis

Report Document - Text Analysis

Appendix Documents

2. Thank You

E-mail user

Mar 20, 2016 20:19:48 Success: Email Sent to: chuanwei.zhang@utdallas.edu